Title: Advanced Klystron Development for High Peak Power and Variable Pulse Structure

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Advanced Klystron Development for High Peak Power and Variable Pulse Structure

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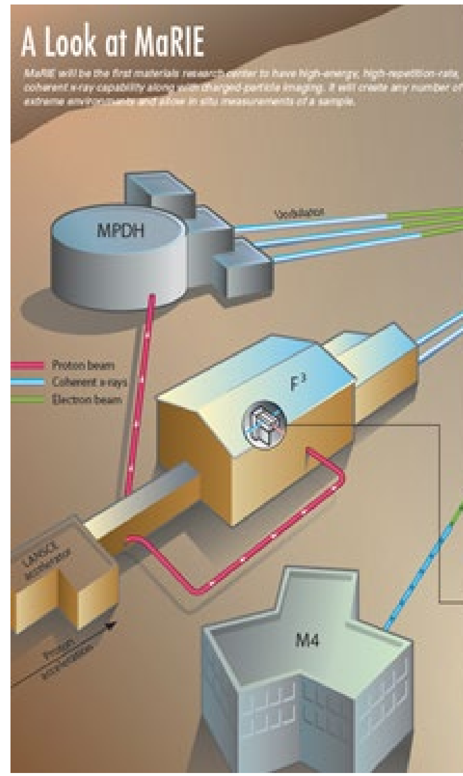
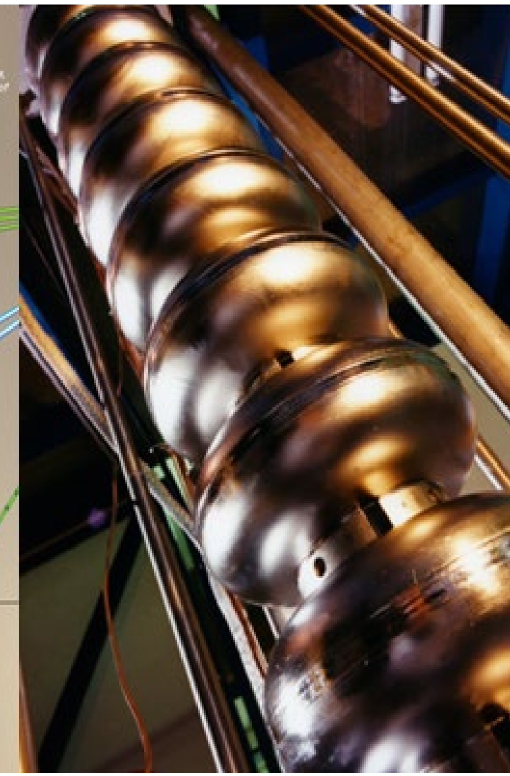
LANL High Gradient Accelerator Research

- MaRIE X-Ray Free Electron Laser (FEL) driven by a 12 GeV electron linear accelerator (LINAC)
- Baseline design uses 1.3 GHz superconducting European XFEL cavities; achievable accelerating gradient is presently ~ 17 MeV/meter
- High Gradient (HG), normal conducting copper structures are getting a second look…
  - Gradients > 150 MeV/m demonstrated
  - Enables up to 10x length reduction; eliminates expensive cryo plant
- MaRIE specific applications, e.g., burst mode radiography, require the superior beam quality of larger C-band 5.7 GHz structures
  - **Burst mode requires either a very flexible RF system, where the pulse repetition can be designed for each experiment**
  - **For a normal conducting machine, this means fast switching of the RF**



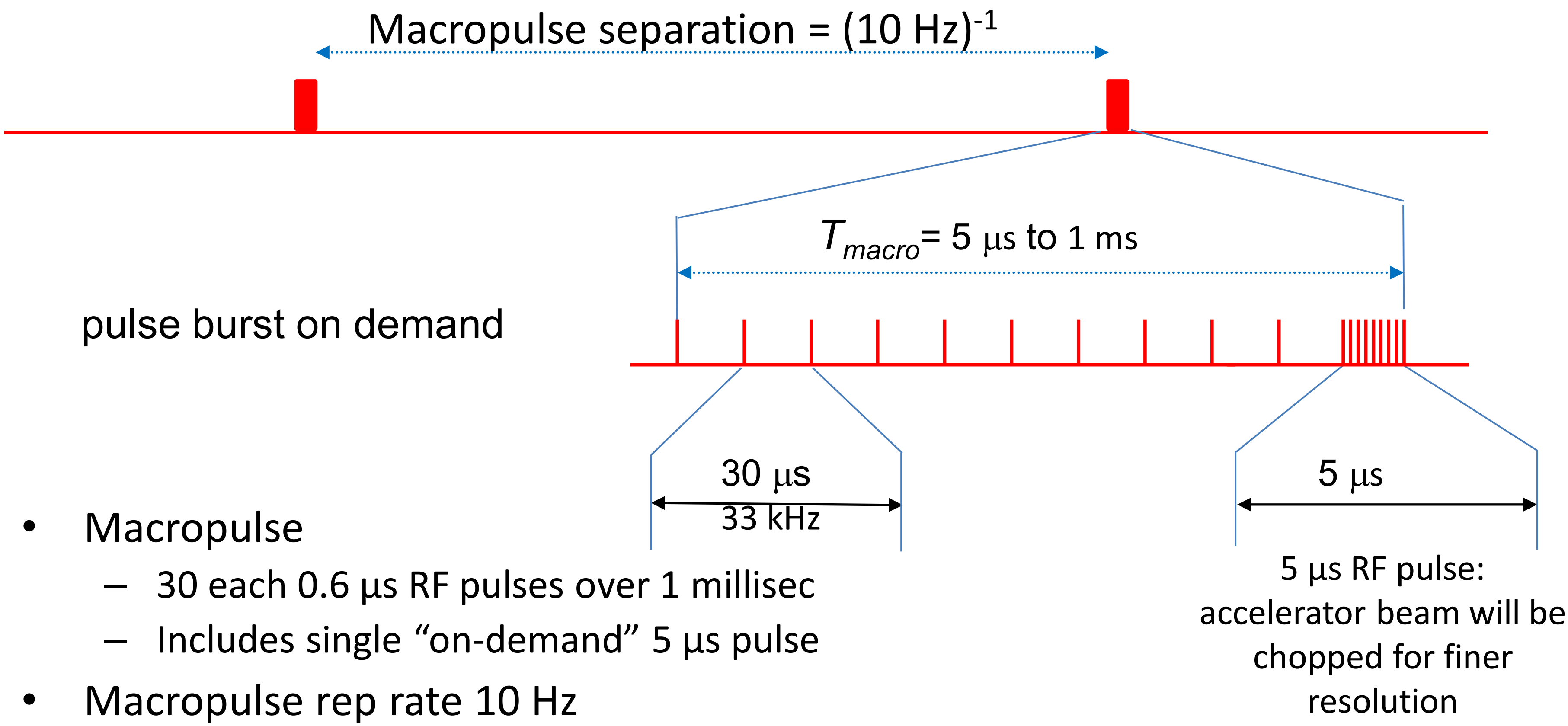
MaRIE: both superconducting and HG normal conducting structures considered



European XFEL superconducting 1.3 GHz cavities at 17 MeV/meter

- A high gradient proton linear accelerator, the world's first, has been proposed for LANSCE pRAD booster
  - The 1970's era LANSCE linac operates at 201 and 805 MHz and is ~ 1 km long; exit proton energy is 800 MeV
  - Energy increase to 3 GeV, provided by a combination of high gradient 2.8175 GHz S- and 5.635 GHz C- band "after burner" cavities, can be achieved with an additional length as short as 20 meters!
  - The ultra short pRAD proton bunch length is compatible with short high gradient cavity RF pulse duration

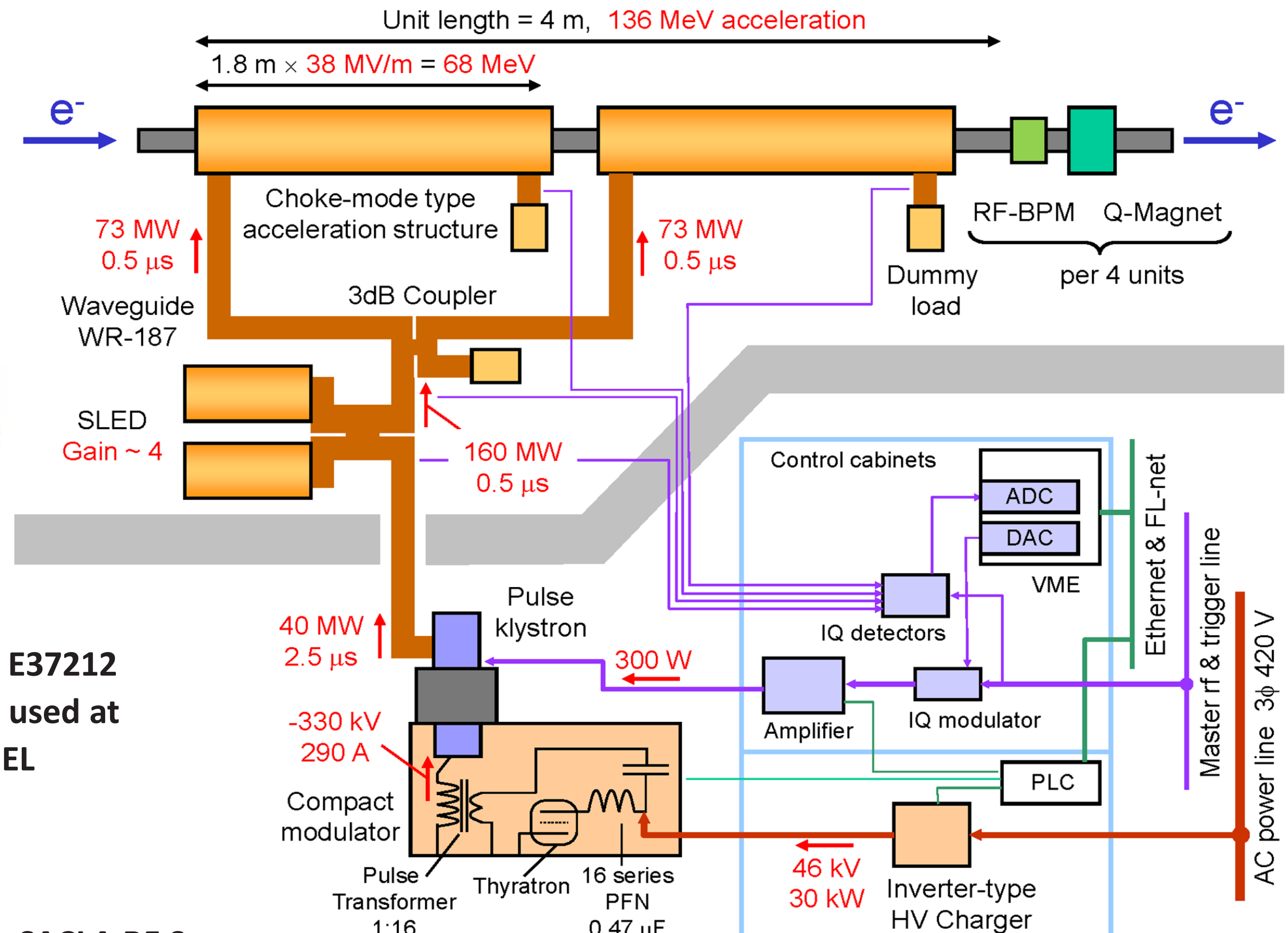
Sample Pulse Format: Imaging Material Phase Changes



- Macropulse
  - 30 each 0.6 μs RF pulses over 1 millisec
  - Includes single "on-demand" 5 μs pulse
- Macropulse rep rate 10 Hz
- Average duty: 23 μs x 10 Hz = 0.023%
- Other pulse formats are of interest: the overall goal is to have flexibility

RF Sources for High Gradient Accelerators
Canon 50 MW C-band Klystrons

Canon E37212 model used at SwissFEL



SACLA RF System

from: T. Inagaki, "High-gradient C-band linac for a compact x-ray free-electron laser facility"

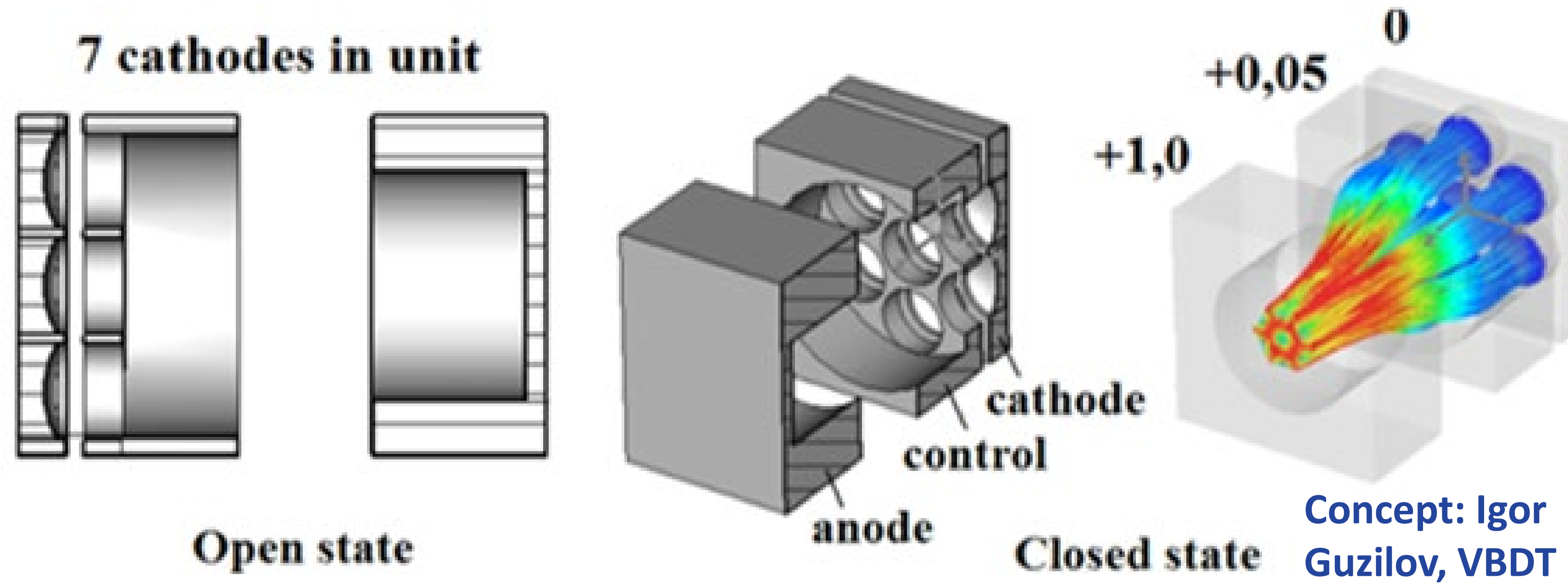
Limitations of Existing Technology

- SwissFEL operation
  - 50 MW peak at 5.712 GHz
  - Diode, cathode pulsed electron gun; E_k = 370 kV, I_k = 324 A
  - 3 µsec RF pulse width @ 100 Hz = 0.03% duty
  - 6.2 µsec beam pulse width @ 100 Hz = 0.062% duty
- Canon Analysis of E37212 for LANL FEL
  - Average LANL RF duty of .023% within current spec
  - Very short beam pulse required to limit collector heat load and mitigate against electron gun HV breakdown; modulator rise & fall times now > 1 µsec; 0.3 µsec needed to avoid collector redesign
  - The 120 MW peak beam power limits klystron operation to very short pulses and low duty
  - 5 µsec final RF pulse length problematic; beam stability uncertain
  - High PRF operation unknown, DC and RF arcing issues possible
- The $\frac{1}{2}CV^2$ energy required to switch the electron gun on and off practically limits rise time and modulation rate

Reduce gate voltage to improve switching agility

- Use a triode gun to allow the klystron electron beam to be gated on and off at a fraction, e.g., 5 percent, of the cathode operating voltage
- A non-intercepting isolated focus electrode surrounding the cathode is the preferred means of controlling emission (a.k.a. aperture gating)
  - A control grid is too delicate for very high power applications
  - The voltage required for a conventional modulating anode is too high
- Use high current density cathodes to decrease cathode diameter and thereby reduce gate voltage
  - The negative, w.r.t. cathode, isolated focus electrode voltage required to cut-off emission is proportional to cathode diameter
  - Conventional M-type dispenser thermionic cathodes are limited to 5 A/cm^2, high current density Nanocomposite Scandate Tungsten (NST) cathodes have been shown to support emission levels of 40 A/cm^2
- Use a Multi Beam Klystron (MBK) architecture to decrease operating voltage relative to a single beam tube, further reducing gate voltage
  - Klystron DC-RF efficiency is also improved as the individual beamlets have lower space charge enabling tighter electron bunch formation
  - An 8-beam MBK operating at Ek = 200 kV, Ik = 400 A (8 x 50 A) is > 70% efficient, producing over 56 MW of peak output power. In contrast the single beam 50 MW Canon E37212 operates at 370 kV, 324 A (42% efficient)

RF Sources for High Gradient Accelerators
Burst Mode Modulation: Gated Mini-Cathodes



- A single isolated focus electrode (FE) is used to modulate emission from several mini-cathodes
- In Guzilov's concept, beamlets converge to create a single, high current beam
- The current plan is to use non-converging individual beamlets from gated mini-cathodes: 8 parallel beamlets interacting with toroidal cavities operating in the TM410 mode

RF Sources for High Gradient Accelerators
Super Power C-Band Multiple Beam Klystron

- High cathode voltage practically limits output power of single beam tubes
- Resonator HOM issues limit frequency of high power MBKs to L-band

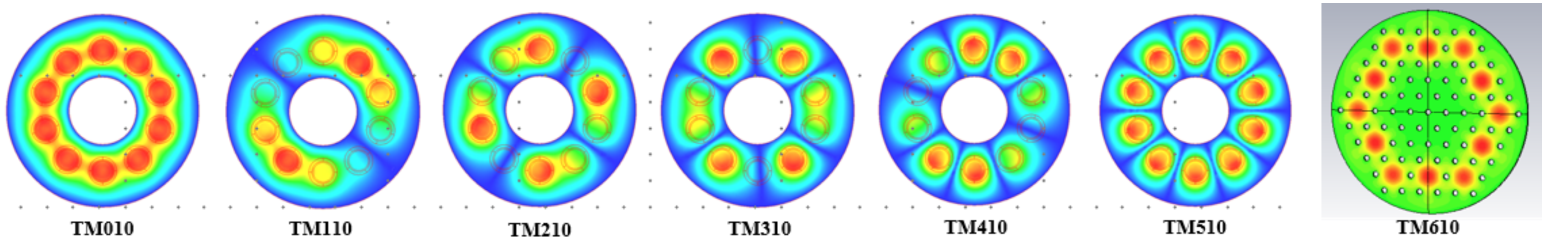
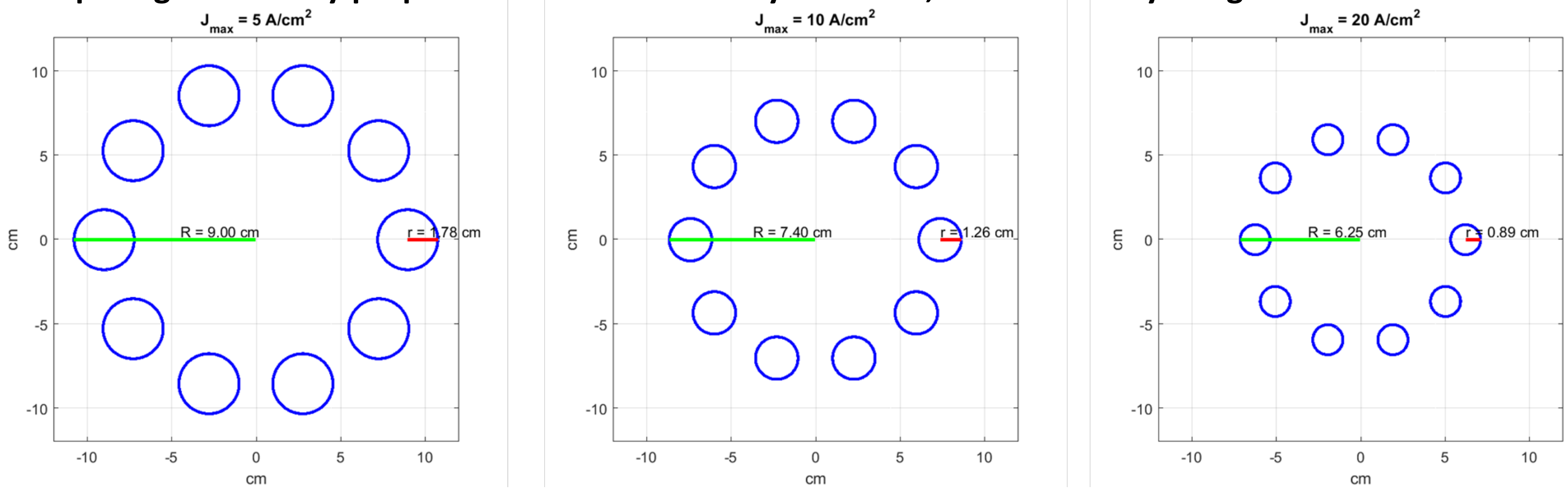


Figure 1: Toroidal cavity TMN10 modes and a Photonic Band Gap cavity with twelve defects for a twelve-beam MBK

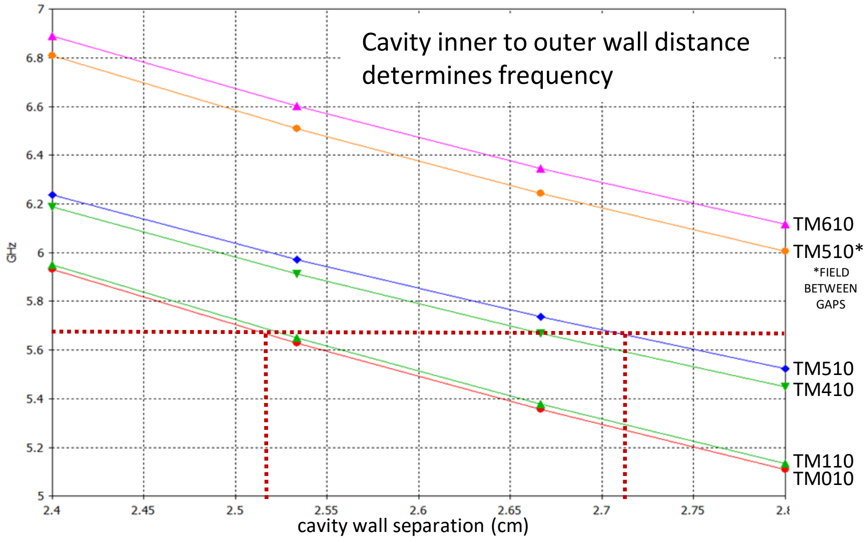
HOM spacing is inversely proportional to overall cavity diameter, determined by the gun radius



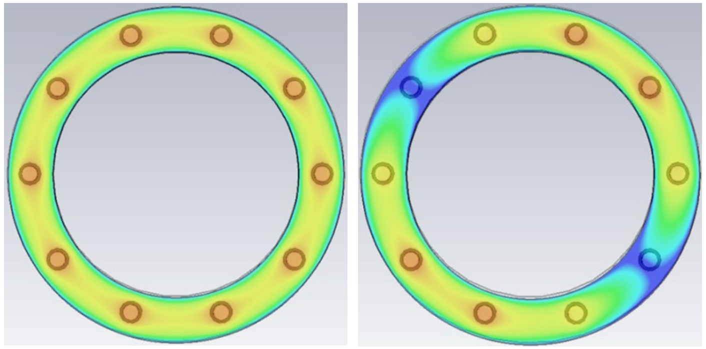
Gun radius as a function of cathode emission density for a 60 MW MBK (200 kV / 500 A)

RF Sources for High Gradient Accelerators
C-Band MBK Resonator Design

- High power MBKs typically use toroidal cavities operating in the fundamental TM010 cavity mode
- Although unorthodox, the TM510 (phase on every other gap reversed) provides greater mode separation for toroidal cavity with the same 14.44 cm drift tube diameter
- TM410 (8 versus 10 beam) ultimately chosen to allow symmetric coupling to two output waveguides placed 180 degrees apart

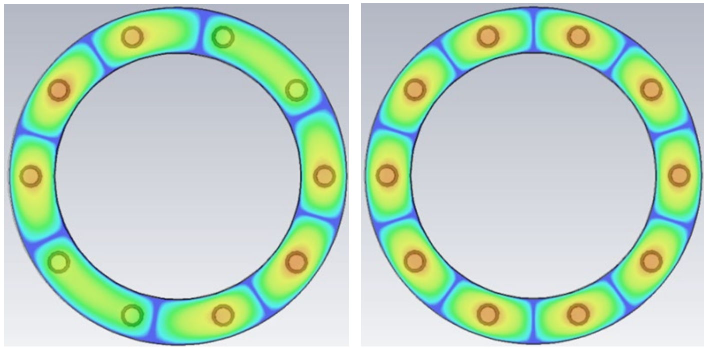


25 MHz TM010 and TM110 mode separation for 5 A/cm^2



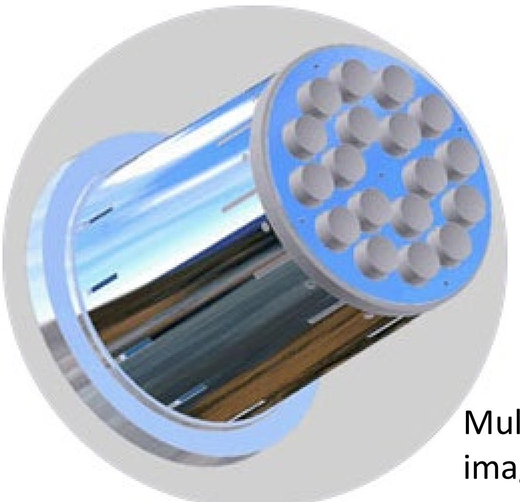
TM010 SYMMETRIC:
E-FIELD IN-PHASE ON
EVERY GAP

75 MHz TM410 and TM510 mode separation for 5 A/cm^2



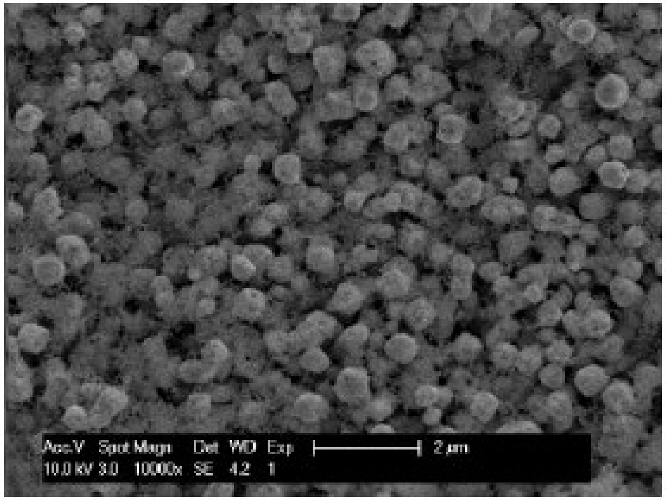
TM510 SYMMETRIC:
E-FIELD REVERSED ON
EVERY GAP

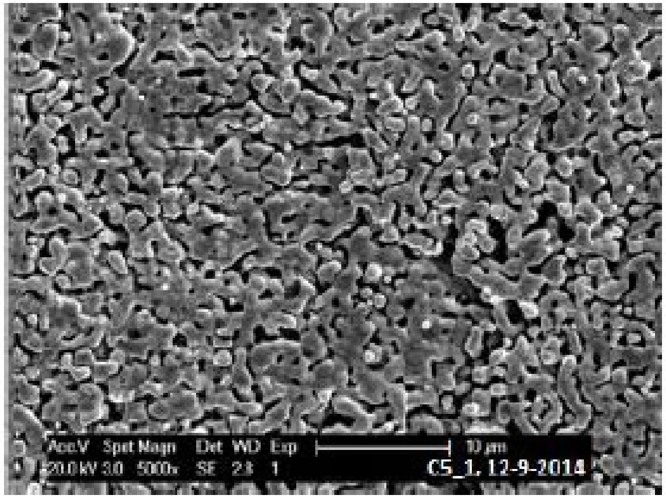
RF Sources for High Gradient Accelerators
C-Band MBK: High Current Density Cathodes



At 1000°C, M-type, Os-Ru coated, barium impregnated, sintered tungsten cathodes, have an emission density of 5 A/cm^2. Super power MBKs need 100s of amps. Higher density cathodes required to reduce electron gun size.

Multiple beam cathode assembly; image from Spectra-Mat, Inc.





UC-Davis photos from D. Gamzina (SLAC)

Nanocomposite Scandate Tungsten (NST) cathodes achieve very high emission densities in laboratory tests. LANL is working with Diana Gamzina to develop a plan to evaluate these cathodes at SLAC, under MBK relevant conditions, to gain confidence that they are capable of providing uniform emission density of 20 to 40 A/cm^2 at ≤ 1000°C, commensurate with 50 khr life.

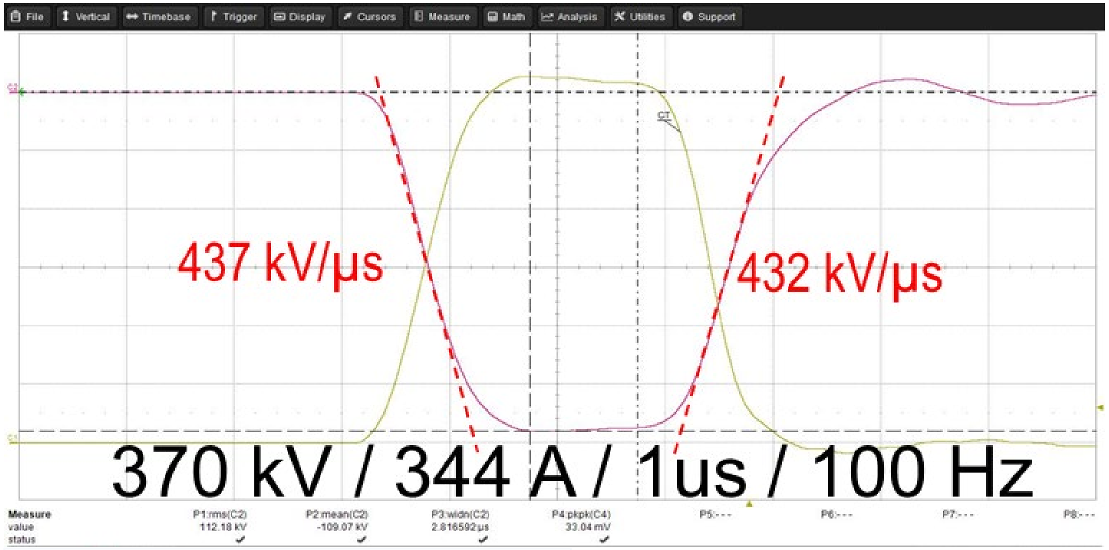
RF Sources for High Gradient Accelerators Summary

- Single beam klystrons are at their limit, high frequency MBKs are needed to meet the extreme peak power requirements of very high gradient structures
  - Resonator HOM issues can be solved by using a TM410 configuration; capacitive loading further separates modes
  - High current density cathodes are an enabling technology
- Pulse burst mode operation is required for the next generation of radiographic imaging applications
  - Existing klystrons use diode guns modulated at full cathode voltage; $\frac{1}{2}CV^2$ losses prevent high rep rate pulsing
  - An MBK fitted with an aperture gated, triode electron gun using high current density cathodes is the best means of achieving on-demand, ultra-fast pulse rates

Backup

RF Sources for High Gradient Accelerators
ScandiNova K2-2 Modulator

SACLA developed their own power supplies, but SwissFEL and now ELI (Extreme Light Infrastructure) use ScandiNova or Ampegon modulators operating at 60 or 100 Hz



ScandiNova K2-2

RF Sources for High Gradient Accelerators
Burst Mode Modulation

- ScandiNova and Ampegon modulators have similar designs
- DC power supplies inject current into several, parallel primary windings
- Pulse transformer multiplies final output voltage
- Saturation of transformer core significantly limits pulse repetition rate

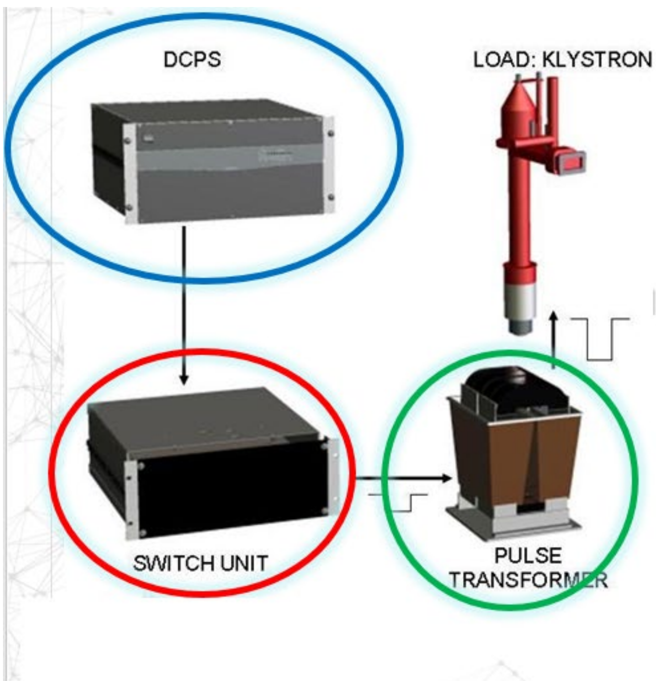
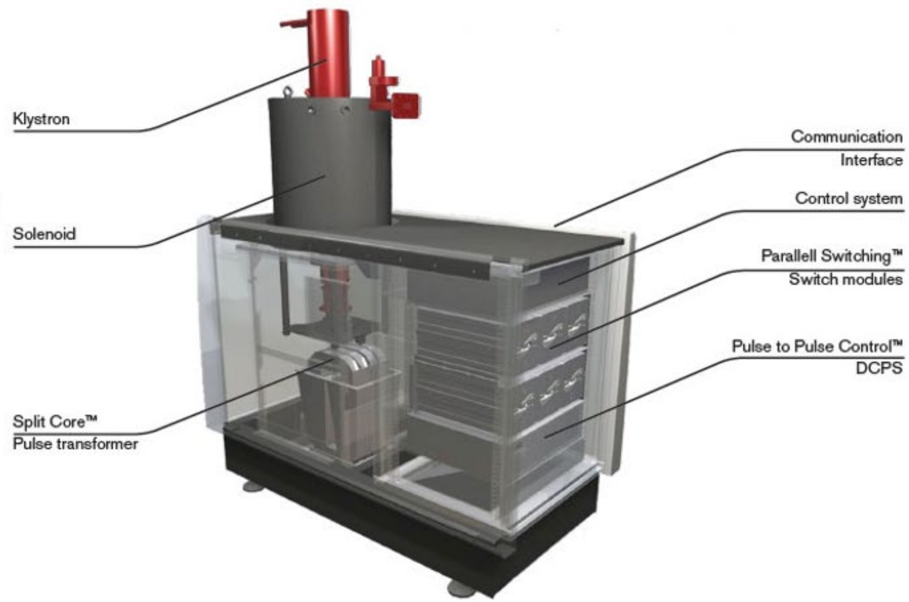
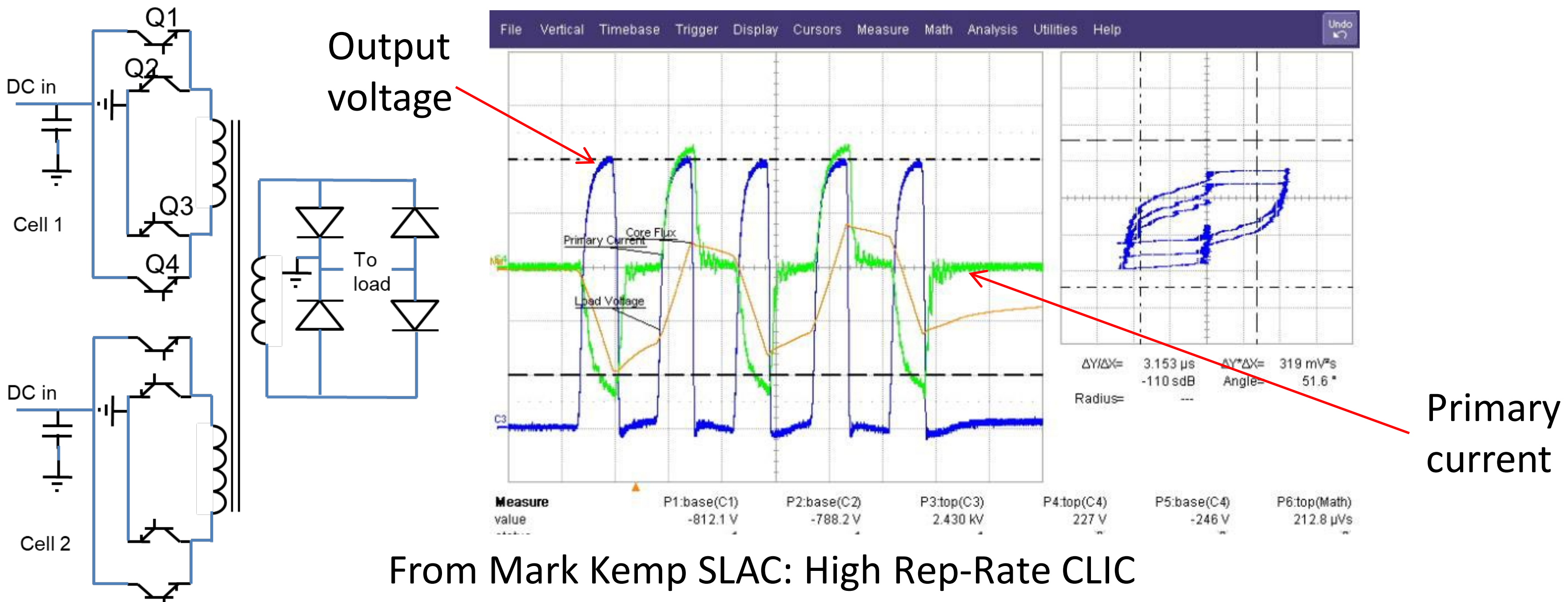


Image courtesy of ScandiNova



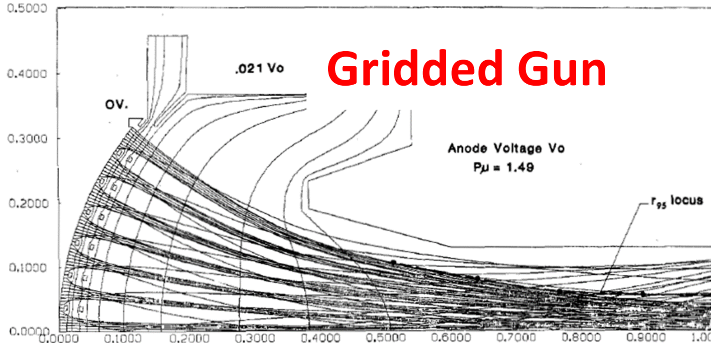
RF Sources for High Gradient Accelerators
Bi-Polar Primary Induction Modulator

- SLAC/CERN concept for CLIC Extraction Kicker 688 kHz burst spec
- Similar to ScandiNova / Ampegon topology, but polarity of primary current injection is reversed on every pulse to re-set transformer core
- Full bridge inverter used to rectify output voltage

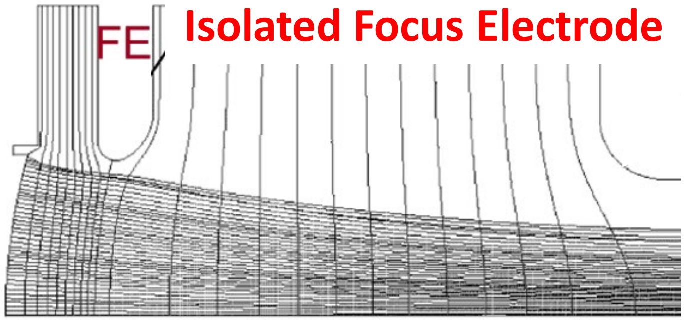


From Mark Kemp SLAC: High Rep-Rate CLIC Combiner Ring Kicker, ALERT 2014 Workshop

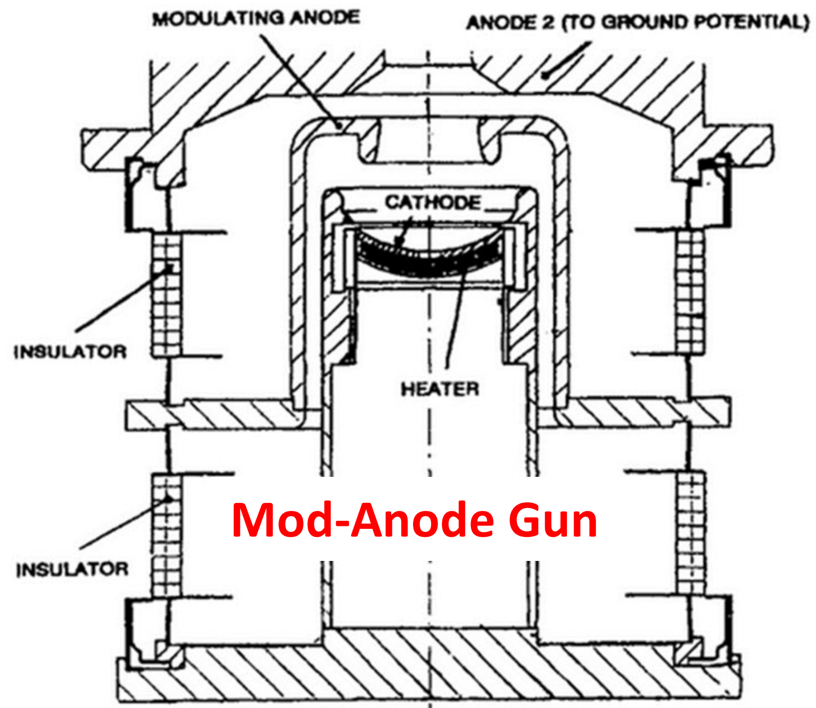
RF Sources for High Gradient Accelerators
Burst Mode Modulation: Triode Guns



- Control grid voltage low
- Not likely to survive the voltage and current required for 50 MW klystrons



- Commonly used in high PRF applications
- Cathode size/current is limited; beam cut-off voltage increases with diameter



Non-intercepting mod-anodes are very robust but require high gate voltage, adversely limiting rise time and PRF

Images from R. Kowalczyk SLAC "RF Source Vacuum Tube Cost," May 2017